

Latest NEMO-3 Results and Status of SuperNEMO

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CNRS/IN2P3 - Université Paris-Sud 11 - LAL Orsay

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NEMO-3

NEMO-3 Experiment

NEMO-3 Results

SuperNEMO

From NEMO-3 to SuperNEMO

SuperNEMO Demonstrator

NEMO-3: the Neutrino Ettore Majorana Observatory



- ▶ Located in the *Laboratoire Souterrain de Modane (LSM)* in France under 4800 m.w.e.
- ▶ Shielded by 30 cm of borated water or wood, 19 cm of pure iron and radon-free air tent (2004)



Phase 1

Feb. 2003 - Oct. 2004

$$A_{int}(^{222}\text{Rn}) \sim 30 \text{ mBq/m}^3$$



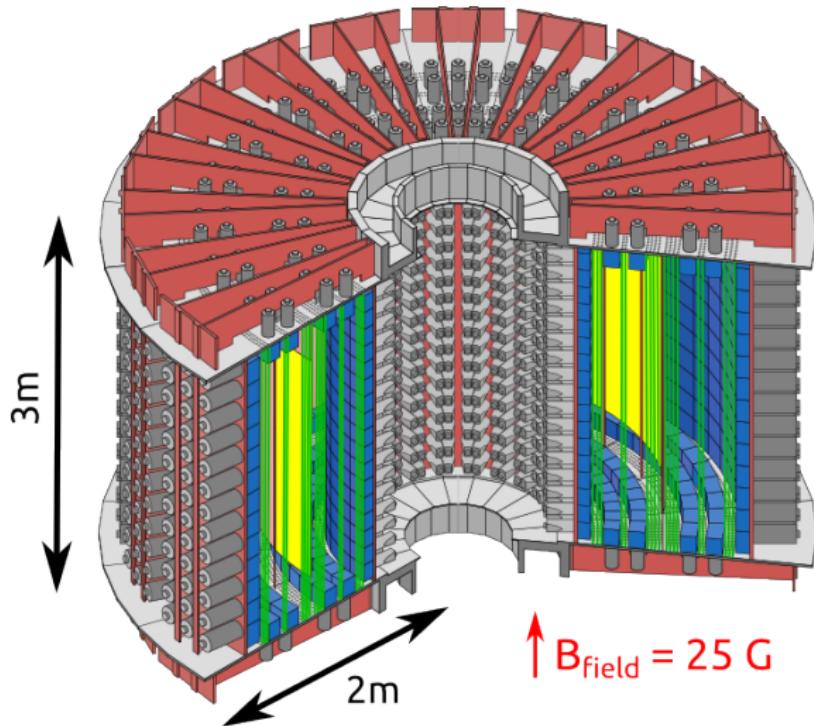
Phase 2

Dec. 2004 - Jan. 2011

$$A_{int}(^{222}\text{Rn}) \sim 5 \text{ mBq/m}^3$$

NEMO-3 Detector

- ▶ NEMO-3 unique tracking and calorimetric double beta decay experiment with 10 kg of sources



sources

60 mg/cm² foils
10 kg of $\beta\beta$ isotopes

tracker

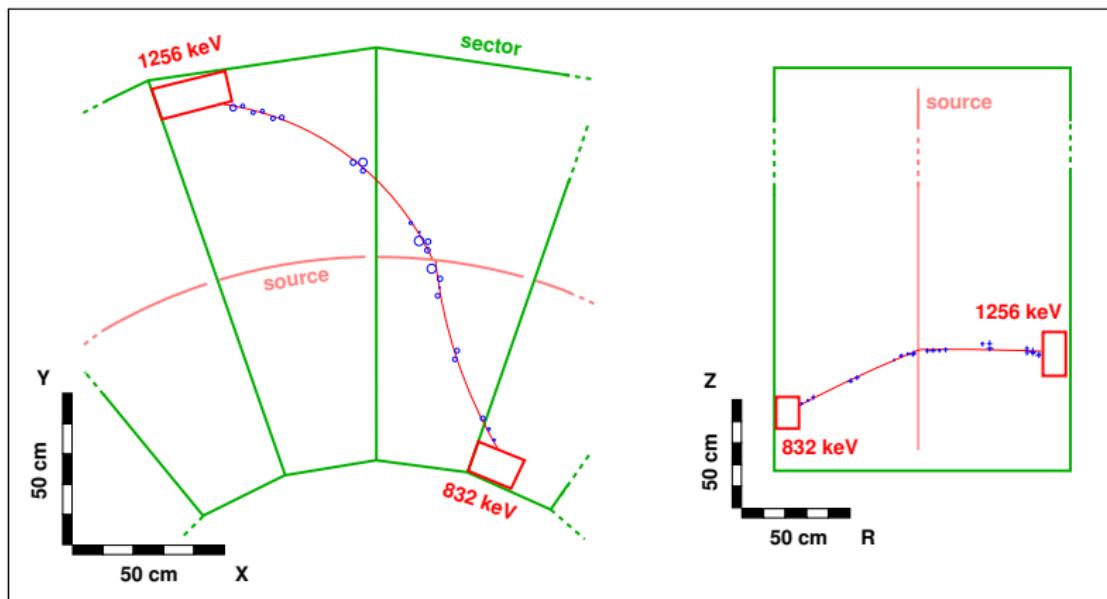
6180 Geiger cells
vertex resolution :
 $\sigma_t = 5 \text{ mm}$ $\sigma_z = 1 \text{ cm}$

calorimeter

1940 counters :
polystyren scintillator
+ 3" and 5" PMTs
 $\text{FWHM}_E = 15\% / \sqrt{E_{\text{MeV}}}$
 $\sigma_T = 250 \text{ ps}$

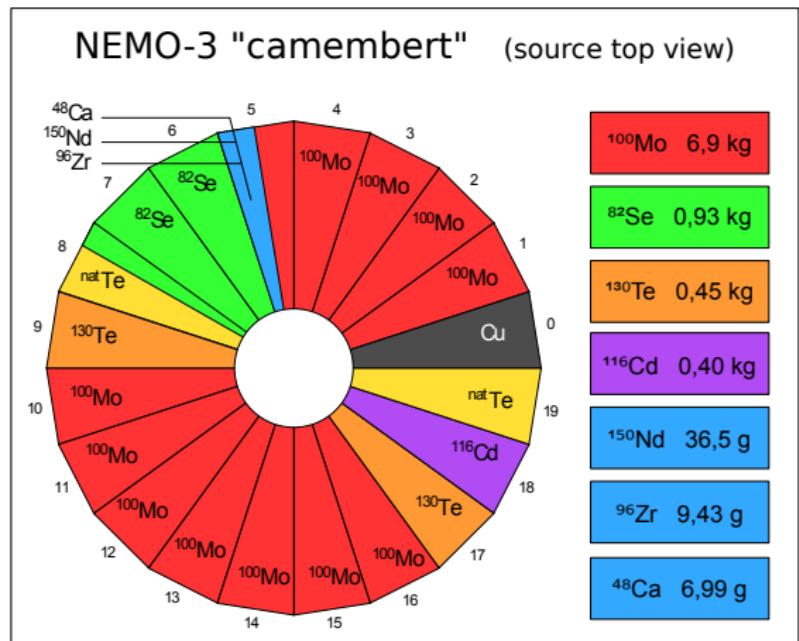
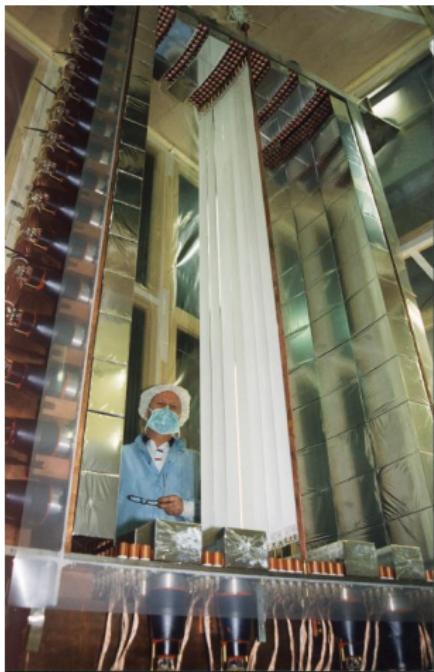
NEMO-3 Unique Features

- ▶ Unique 2β experiment with the direct reconstruction of the $2e^-$
→ full signature of $0\nu 2\beta$ events and powerful background rejection
- ▶ Individual electron energies (E_1, E_2), time of arrival (t_1, t_2),
curvature in magnetic field (\pm), emission vertex and angle ($\cos \theta$)
- ▶ Modest energy resolution and efficiency
- ▶ Background for $0\nu 2\beta$ equivalent to the best calorimeter experiments



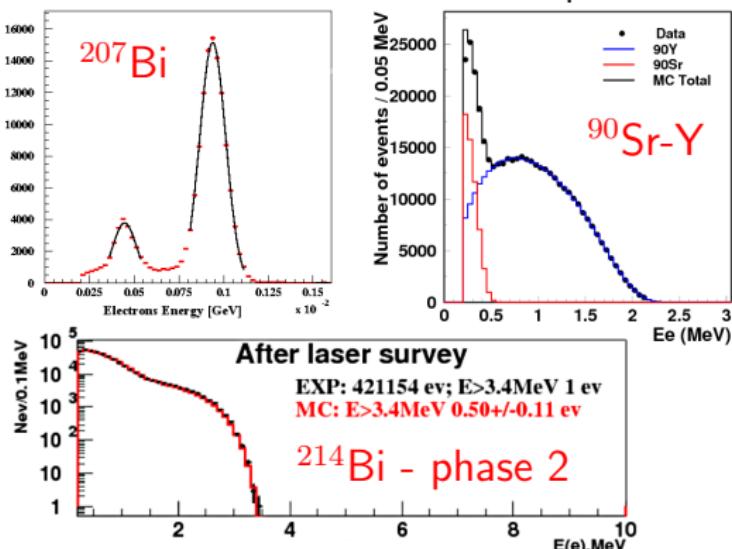
NEMO-3 Sources

- ▶ NEMO-3 technique allows to study most of the double beta decay isotopes



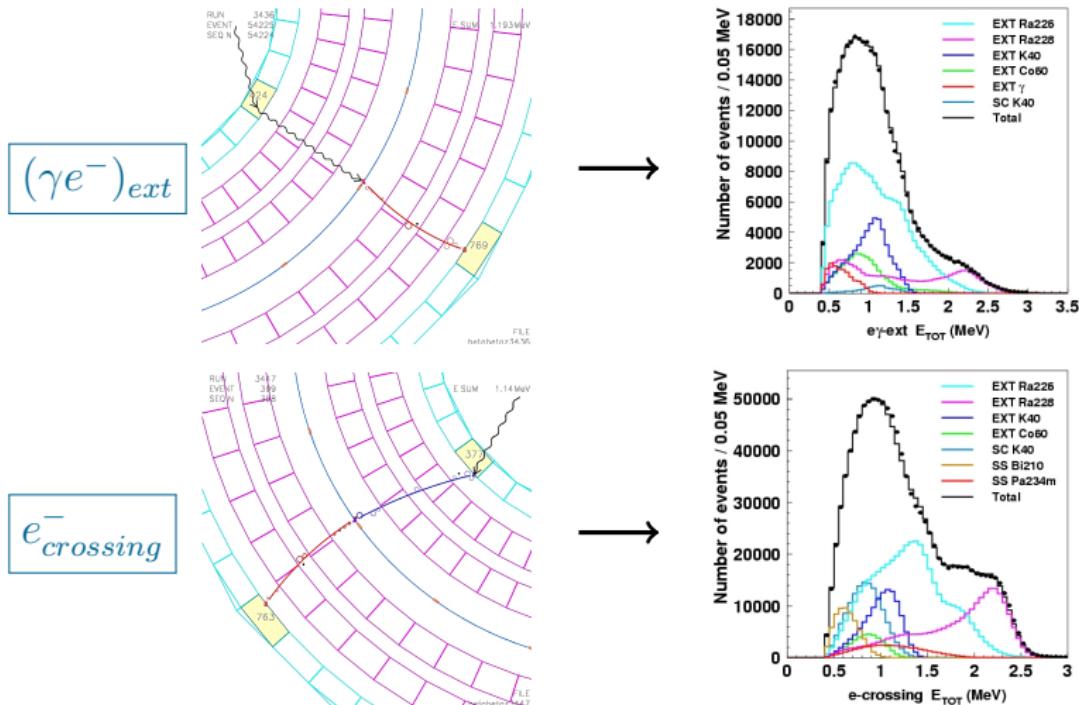
NEMO-3 Calibrations

- ▶ 20 calibration tubes close to foils for 60 sources at 3 heights:
 - ▶ ^{207}Bi : 482 and 976 keV conversion electrons every 3 weeks
 - ▶ $^{90}\text{Sr-Y}$: end-point of the electron spectrum ($Q_\beta = 2.28 \text{ MeV}$)
- ▶ Light injection to each calorimeter block through optical fibers:
 - ▶ linearity better than 1 % between 0 and 4 MeV
 - ▶ PMT gain and time stability survey twice a day (99 % PMTs < 2 %)
- ▶ $^{214}\text{Bi} e^-$ end-point ($Q_\beta = 3.27 \text{ MeV}$) to validate the PMT stability:
 - ▶ 3 events $e^- \alpha$ observed above 3.4 MeV for 2.5 ± 0.3 expected



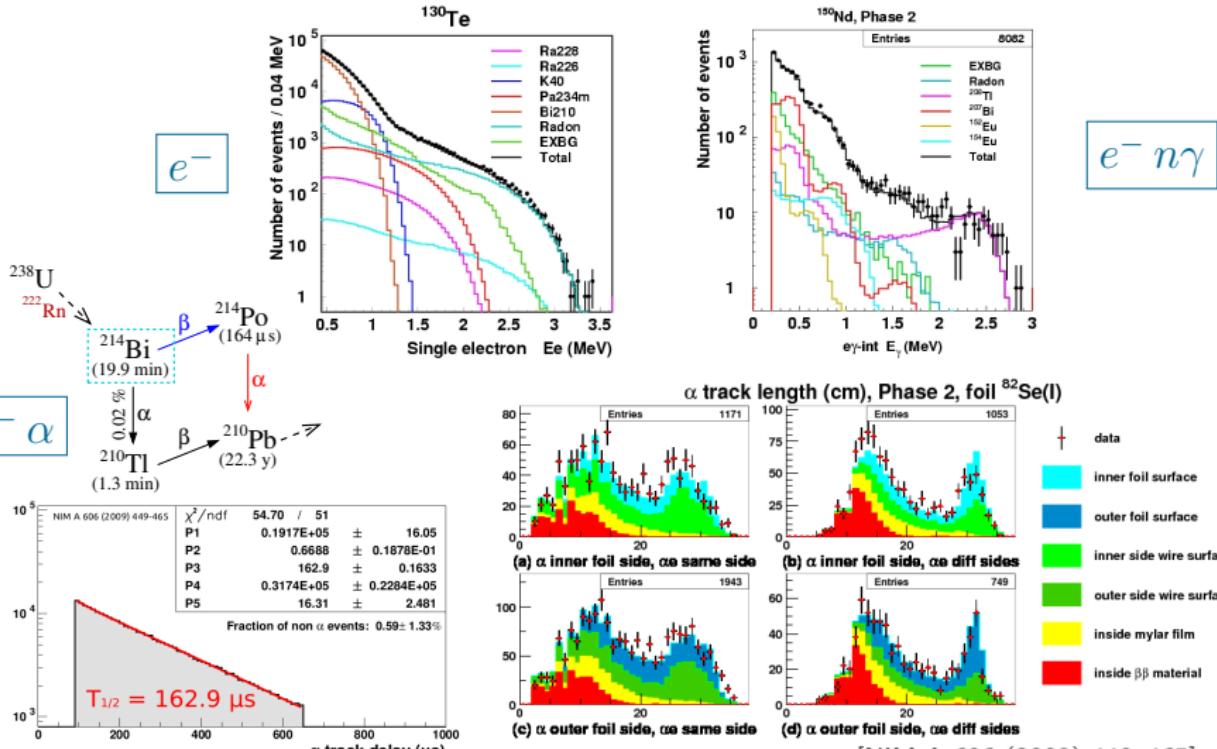
NEMO-3 External Background Measurements

- ▶ Natural radioactivity backgrounds (γ , n) from detector components or surroundings and cosmic rays (μ , n)
- ▶ Particle identification: e^- , e^+ , γ , μ and *external TOF*
- ▶ Direct measurements with 2 main analysis channels:

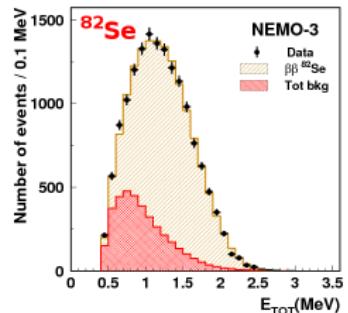


NEMO-3 Internal Background Measurements

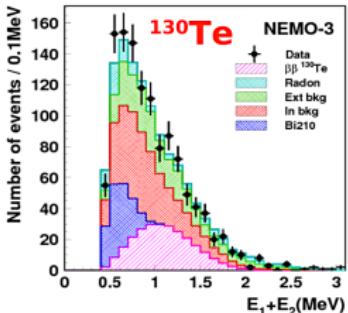
- ▶ Radioactive contaminations of the foil (^{214}Bi , ^{208}Tl ...) and Radon
- ▶ Particle identification: e^- , e^+ , γ , α and *internal TOF*
- ▶ Direct measurements through several analysis channels:



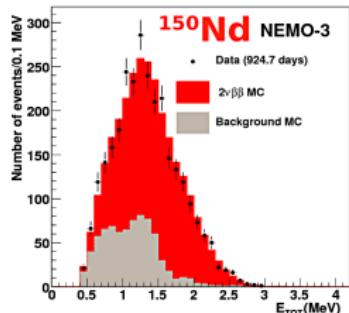
NEMO-3 $2\nu 2\beta$ Measurement of Lower Mass Isotopes



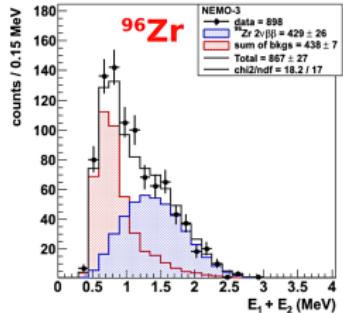
$T_{1/2} = 9.6 \pm 1.0 \cdot 10^{19}$ y
PRL 95, 182302 (2005)



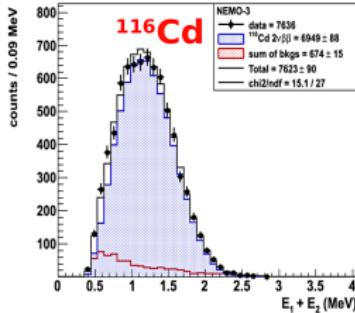
$T_{1/2} = 7.0 \pm 1.4 \cdot 10^{20}$ y
PRL 107, 062504 (2011)



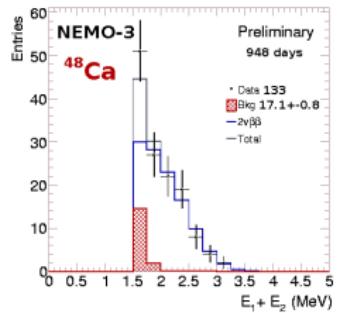
$T_{1/2} = 9.1 \pm 0.7 \cdot 10^{18}$ y
Phys. Rev. C 80, 032501 (2009)



$T_{1/2} = 2.35 \pm 0.21 \cdot 10^{19}$ y
Nucl. Phys. A 847, 168 (2010)



$T_{1/2} = 2.9 \pm 0.3 \cdot 10^{19}$ y
To be published



$T_{1/2} = 4.4 \pm 0.6 \cdot 10^{19}$ y
Systematics under study

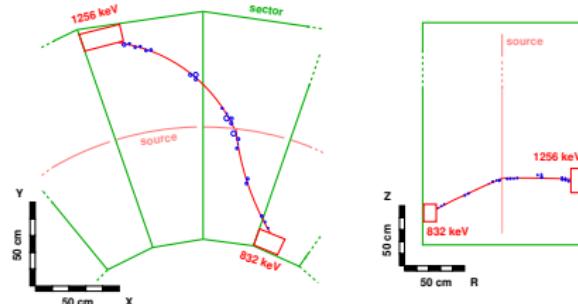
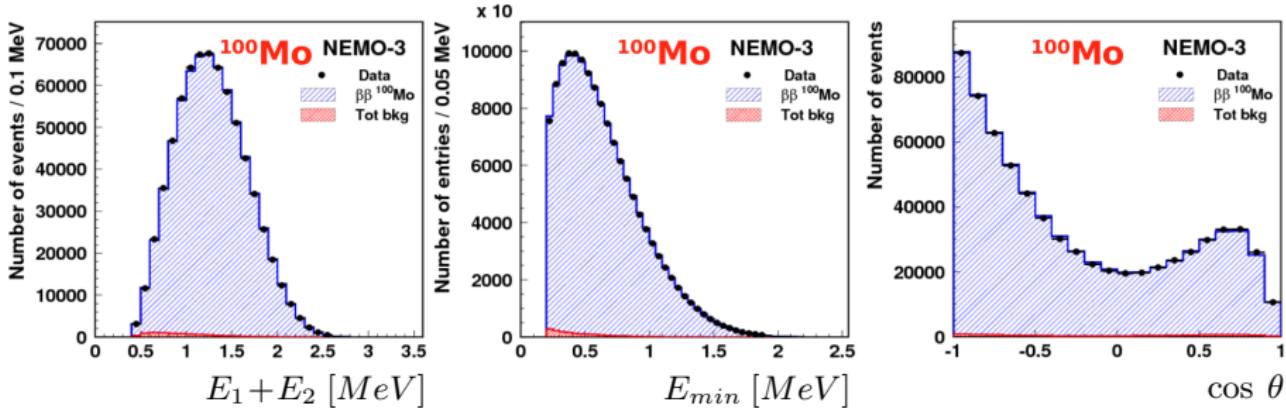
NEMO-3 $2\nu 2\beta$ of ^{100}Mo Measurement

- ▶ 700 000 events of $2\nu 2\beta$ with 7 kg of ^{100}Mo :

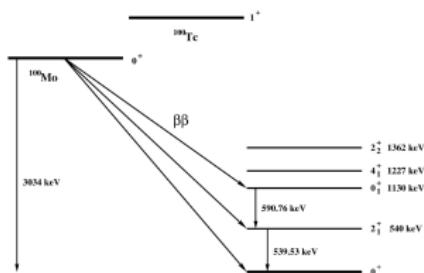
S/B = 76 - $\mathcal{E}_{2\nu} = 4.3 \%$

$$\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst)} 10^{18} \text{ y}$$

[Phys. Rev. Lett. 95, 182302 (2005)]



NEMO-3 Double Beta Decay to Excited States



$2\nu 2\beta$ to excited states of ^{100}Mo :

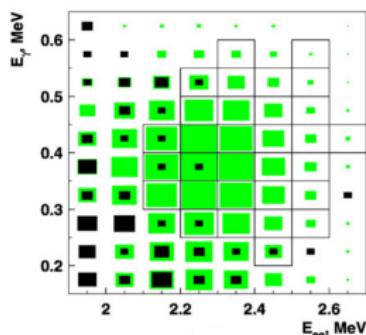
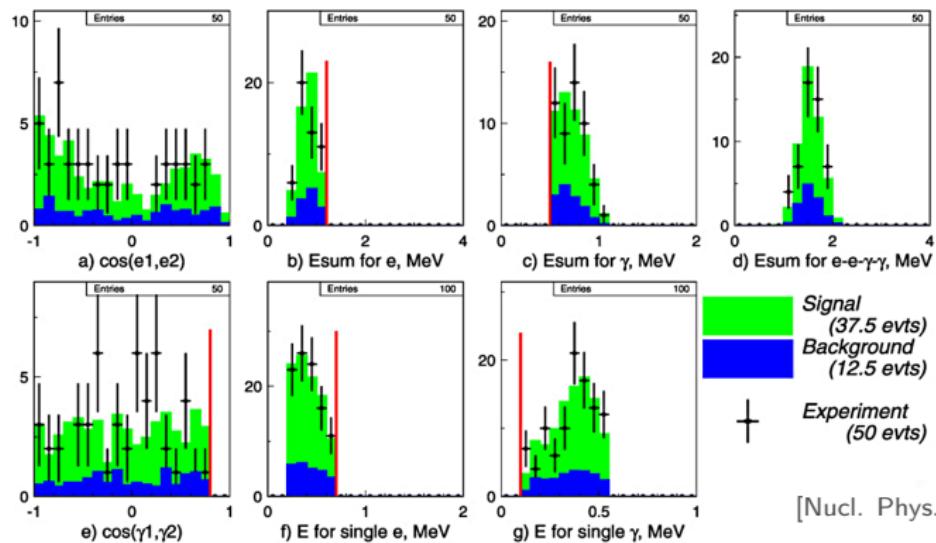
$$\mathcal{T}_{1/2}^{2\nu}(0^+ \rightarrow 0_1^+) = 5.7_{-0.9}^{+1.3} \text{ (stat)} \pm 0.8 \text{ (stat)} 10^{20} \text{ y}$$

$$\mathcal{T}_{1/2}^{2\nu}(0^+ \rightarrow 2_1^+) > 1.1 10^{21} \text{ y @ 90 % CL}$$

$0\nu 2\beta$ to excited states of ^{100}Mo :

$$\mathcal{T}_{1/2}^{0\nu}(0^+ \rightarrow 0_1^+) > 8.9 10^{22} \text{ y @ 90 % CL}$$

$$\mathcal{T}_{1/2}^{0\nu}(0^+ \rightarrow 2_1^+) > 1.6 10^{23} \text{ y @ 90 % CL}$$



[Nucl. Phys. A 781 (2007) 209-226]

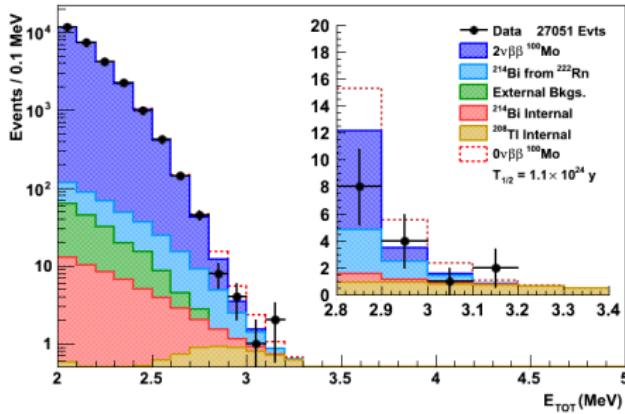
► Other results coming soon on ^{150}Nd and ^{96}Zr

NEMO-3 $0\nu 2\beta$ Mass Mechanism Search with ^{100}Mo

- Total ^{100}Mo exposure of 34.7 kg·y gave no event excess:

$$\mathcal{T}_{1/2}^{0\nu} > 1.1 \cdot 10^{24} \text{ y} \quad (90\% \text{ CL}) \text{ corresponding to } |m_{\beta\beta}| < 0.3 - 0.8 \text{ eV}^*$$

NEMO-3 - ^{100}Mo - 7 kg, 4.96 y

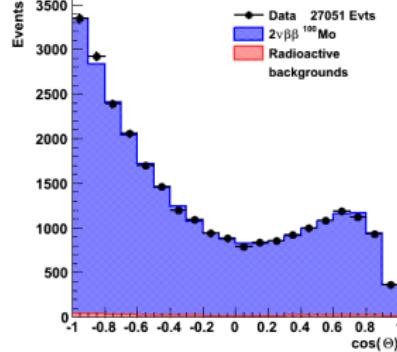
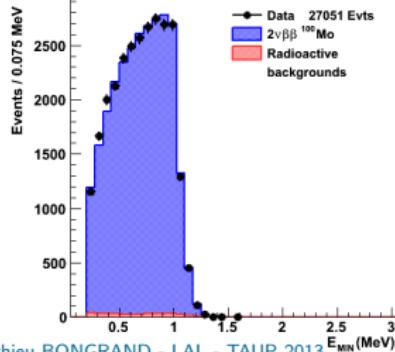


[Including systematics]

Expected background in [2.8 – 3.2] MeV

$2\nu 2\beta$	8.4 ± 0.1
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.2
^{208}Tl internal	3.4 ± 0.3
Total	18.0 ± 0.6
Data	15

[To be submitted to Phys. Rev. Lett. Sept 2013]



* NME:

- M. Kortelainen et al., Phys. Rev. C 76 (2007) 024315
 F. Šimkovic et al, Phys. Rev. C 87 (2013) 045501
 J. Barea et al., Phys. Rev. C 79 (2009) 044301
 P. K. Rath et al., Phys. Rev. C 82 (2010) 064310

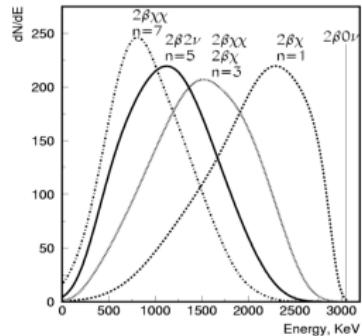
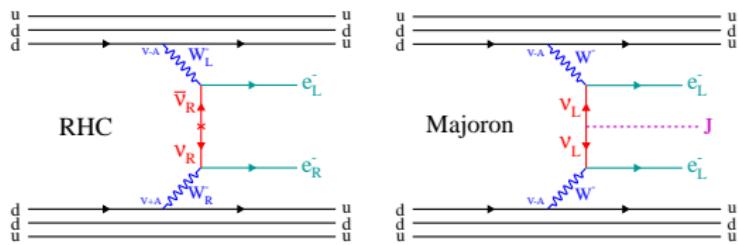
NEMO-3 Other $0\nu 2\beta$ LNV Processes Search

$$(\mathcal{T}_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 \chi^2 \quad \text{where} \quad \chi = |m_{\beta\beta}|, \langle \lambda \rangle, \langle \eta \rangle, \langle g_M \rangle$$

- ▶ Upper limits at 90 % CL set on the search for other $0\nu 2\beta$ Lepton Number Violating processes with ^{100}Mo in units of 10^{24} y:

$0\nu 2\beta$ Process	Only Statistical	Including Systematics	Expected	Physics Parameters*
Mass mechanism $ m_{\beta\beta} $	1.1	1.1	1.0	0.3 - 0.8 eV
Right-handed current $\langle \lambda \rangle$	0.7	0.6	0.5	$1 \cdot 10^{-6}$
Right-handed current $\langle \eta \rangle$	1.0	1.0	0.9	$0.8 \cdot 10^{-8}$
Majoron emission $\langle g_M \rangle$	0.05	0.04	0.04	$2 - 5 \cdot 10^{-5}$

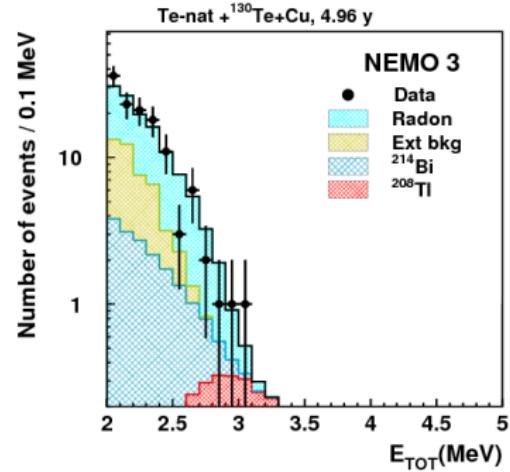
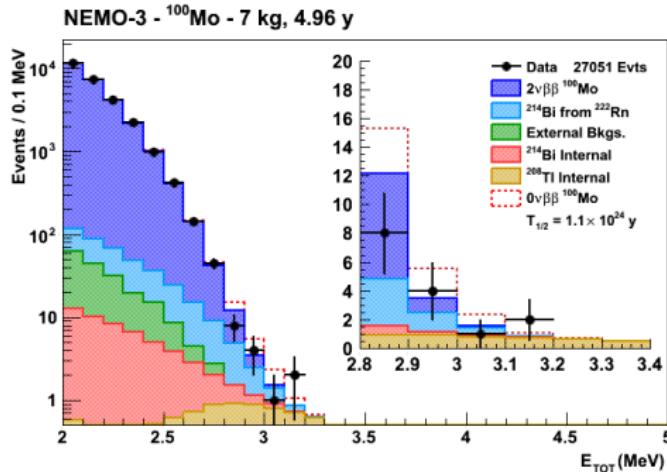
[To be submitted to Phys. Rev. Lett. Sept 2013]



* NME: Mass mechanism on previous slide - J. Suhonen, Nucl. Phys. A700 (2002) 649 - P. K. Rath et al., arXiv:1308.0460
- F. Šimkovic et al, Phys. Rev. C 60 (1999) 055502

NEMO-3 Very Low Background Experiment

- At high energy we can test the backgrounds for the $0\nu 2\beta$ search



[To be submitted to Phys. Rev. Lett. Sept 2013]

- No events in ^{100}Mo after 34.7 kg·y exposure above 3.2 MeV
- No events in copper and natural tellurium samples after 13.5 kg·y exposure above 3.1 MeV
- **Background free technique for high energy $Q_{\beta\beta}$ isotopes:**
 ^{48}Ca : 4.272 MeV, ^{150}Nd : 3.368 MeV or ^{96}Zr : 3.350 MeV
→ SuperNEMO

NEMO-3

NEMO-3 Experiment

NEMO-3 Results

SuperNEMO

From NEMO-3 to SuperNEMO

SuperNEMO Demonstrator

From NEMO-3 to SuperNEMO

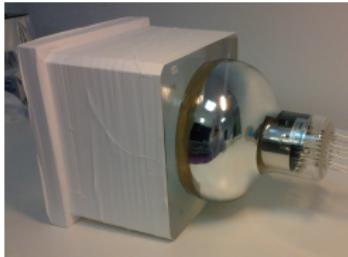
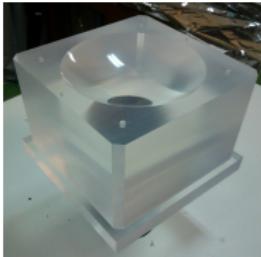
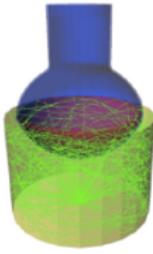


	NEMO-3	SuperNEMO
Mass	7 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
Foil density	7 isotopes 60 mg/cm ²	$^{150}\text{Nd}, ^{48}\text{Ca}$ 40 mg/cm ²
Energy resolution (σ FWHM)		
@ 1 MeV	6.3 15 %	3.0 7 %
@ 3 MeV	3.4 8 %	1.7 4 %
Radon in tracker		
$\mathcal{A}(^{222}\text{Rn})$	$\sim 5.0 \text{ mBq/m}^3$	$\sim 0.15 \text{ mBq/m}^3$
Sources contaminations		
$\mathcal{A}(^{208}\text{Tl})$	$\sim 100 \mu\text{Bq/kg}$	< 2 $\mu\text{Bq/kg}$
$\mathcal{A}(^{214}\text{Bi})$	60 - 300 $\mu\text{Bq/kg}$	< 10 $\mu\text{Bq/kg}$
Detector		
tracking cells	6180	20×2034
calo blocks	1940	20×712
Sensitivity (90 % CL)		
$T_{1/2}^{0\nu}$	$> 1.1 \cdot 10^{24} \text{ y}$	$> 1 \cdot 10^{26} \text{ y}$
$ m_{\beta\beta} $	< 0.3 - 0.8 eV	< 40 - 100 meV

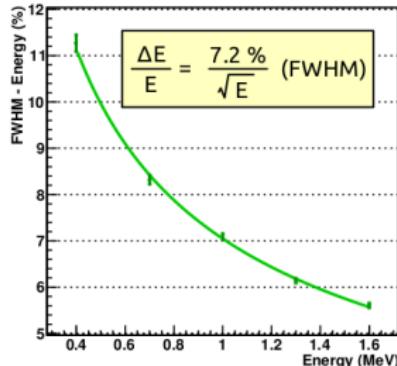
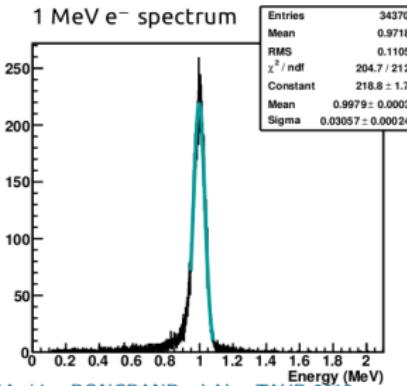
SuperNEMO demonstrator module with 7 kg of ^{82}Se (53 mg/cm²) is under construction

SuperNEMO Calorimeter Improvement

- Energy resolution of 7 % FWHM at 1 MeV achieved:
 - High QE large 8" PMTs (Hamamatsu R5912) directly coupled to the scintillator (no light guide) and improved HV divider
 - PVT plastic scintillators (also 8 % achieved for PS)
 - Optimization of the scintillator blocks geometry
 - Electronics sampling the PMT pulses ~ 2 GS/s (MatAcq/SNFEB)



1 MeV e^- spectrum



Reduce the Radon Background

- ▶ Goal: reduce the internal radon background to 0.15 mBq/m^3
- ▶ Facilities to select detector materials and protections (seals, films...)



Bordeaux emanation tank

Bratislava emanation setup

Prague permeability setup

- ▶ Facilities to measure the radon level in the detector or gases



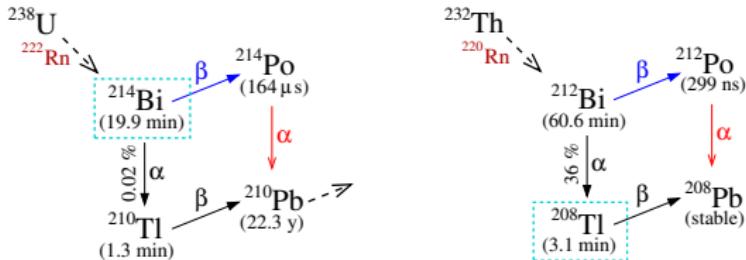
Several electrostatic detectors



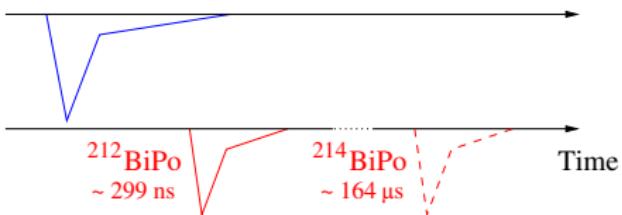
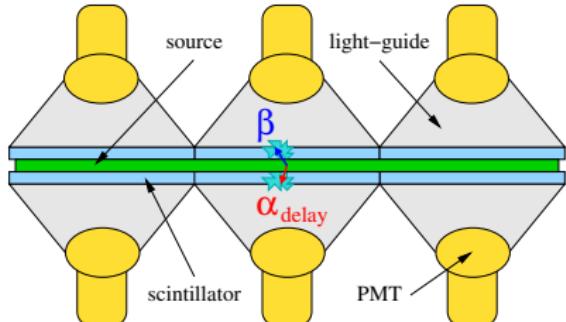
London concentration line

Measure the Radiopurity of the SuperNEMO Sources

- ▶ HPGe γ spectroscopy not sufficient to reach few $\mu\text{Bq}/\text{kg}$ today (factor 50 improvement needed for thin foils)
- ▶ Main contaminations for $0\nu 2\beta$ search (^{214}Bi and ^{208}Tl) measured through BiPo processes from natural radioactivity chains:

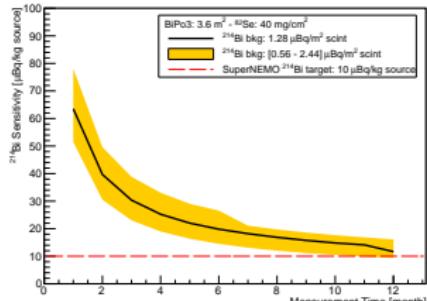
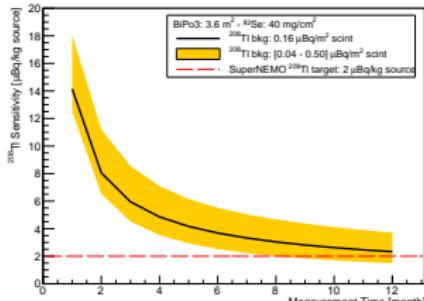
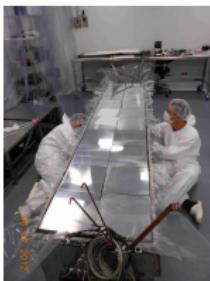
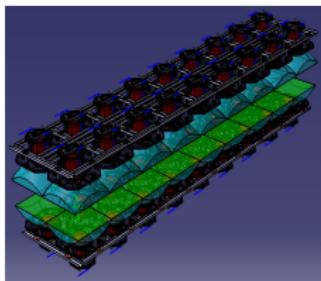


- ▶ β and α particles detected by thin radiopure plastic scintillators coupled to light-guides and low radioactivity PMTs:



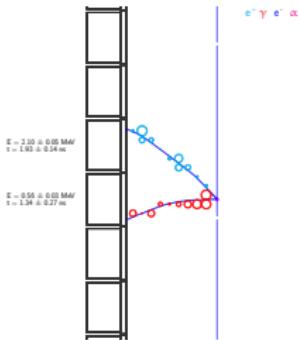
The BiPo3 Detector

- ▶ 2 modules of $3.0 \times 0.6 \text{ m}^2$ can measure 1.4 kg of ^{82}Se foil (40 mg/cm^2)
- ▶ 2 mm thick aluminized polystyrene scintillators, PMMA light guides and 5" Hamamatsu low radioactivity PMTs
- ▶ PMT pulses digitized by MatAcq boards and dedicated trigger board
- ▶ Running since 2012 in Canfranc Underground Lab (LSC, Spain)
- ▶ Sensitivity: $^{208}\text{Tl} < 2 \mu\text{Bq/kg}$ and $^{214}\text{Bi} < 10 \mu\text{Bq/kg}$

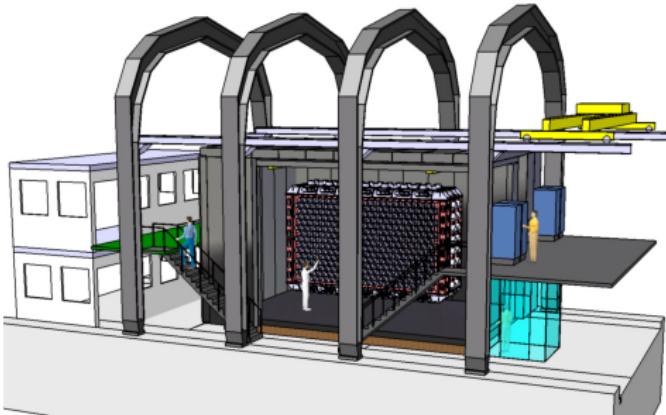
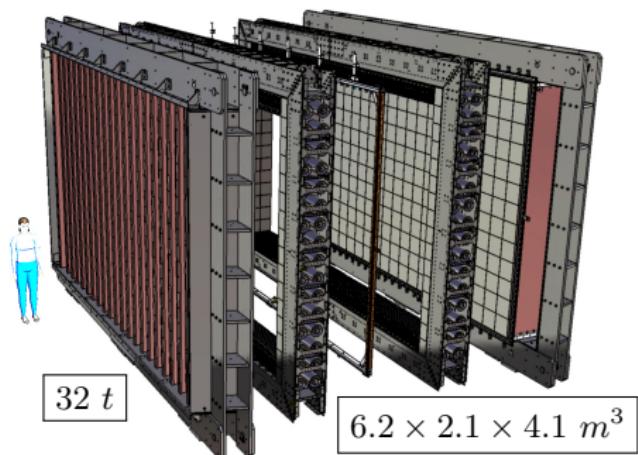


SuperNEMO Demonstrator

- ▶ SuperNEMO demonstrator module construction started in 2012
 - ▶ NEMO-3 sensitivity in only 5 months (90 % CL):
 $(T_{1/2}^{0\nu} > 1.1 \cdot 10^{24} \text{ y} \rightarrow |m_{\beta\beta}| < 0.3 - 0.8 \text{ eV})$
 - ▶ No background in the $0\nu 2\beta$ region in 2.5 years for 7 kg of ^{82}Se
 - ▶ Sensitivity after 17.5 kg·y exposure (90 % CL):
 $T_{1/2}^{0\nu} > 6.5 \cdot 10^{24} \text{ y} \rightarrow |m_{\beta\beta}| < 200 - 400 \text{ meV}$
- ▶ Commissioning in the actual LSM expected end of 2014



Replacing NEMO-3 in the actual LSM

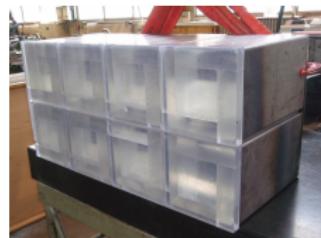
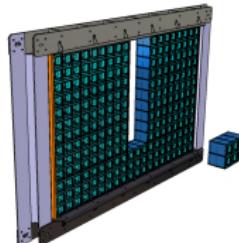


SuperNEMO Demonstrator Construction Status

- ▶ Scintillators under production and 8" Hamamatsu PMTs in 02/2014
- ▶ FE digitizer boards OK, control and trigger boards under development
- ▶ Blocks, wall designs and mechanical tests OK → construction starting!

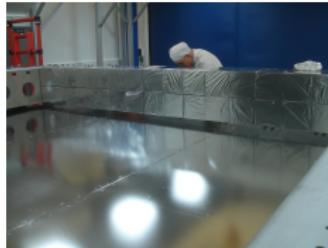
Calorimeter

$256 \times 256 \times 194 \text{ mm}^3$



Tracker

- ▶ Automated drift cells production ongoing with the wiring robot
- ▶ First 1/4 tracker C0 under radon emanation test before cells population
- ▶ C0 commissioning: sea-level end of 2013 and underground in 2014



Sources

- ▶ Already 5.5 kg of enriched ^{82}Se with 0.5 kg purified
- ▶ Source materials (glue, films...) under HPGe and BiPo selection processes
- ▶ Calibration sources deployment system prototype under test

Summary

NEMO-3:

- ▶ Unique 2β experiment with the direct reconstruction of the $2e^-$
→ full signature of $0\nu2\beta$ events and powerful background rejection
- ▶ Total ^{100}Mo exposure of $34.7 \text{ kg}\cdot\text{y}$ gave no event excess:
 $\mathcal{T}_{1/2}^{0\nu} > 1.1 \cdot 10^{24} \text{ y}$ (90 % CL) corresponding to $|m_{\beta\beta}| < 0.3 - 0.8 \text{ eV}^*$
- ▶ Upper limits set on the search for other $0\nu2\beta$ Lepton Number Violating processes with ^{100}Mo
- ▶ Background free technique for high energy $Q_{\beta\beta}$ isotopes

SuperNEMO demonstrator with 7 kg of ^{82}Se under construction:

- ▶ Commissioning end of 2014 and physics data in 2015
- ▶ No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se
- ▶ Sensitivity after $17.5 \text{ kg}\cdot\text{y}$ exposure (90 % CL):
 $\mathcal{T}_{1/2}^{0\nu} > 6.5 \cdot 10^{24} \text{ y} \rightarrow |m_{\beta\beta}| < 200 - 400 \text{ meV}$

Full SuperNEMO with 100 kg of ^{82}Se :

$$\mathcal{T}_{1/2}^{0\nu} > 1 \cdot 10^{26} \text{ y} \rightarrow |m_{\beta\beta}| < 40 - 100 \text{ meV}$$